

OPTIMIZATION OF FLY ASH REPLACEMENT
IN
HIGH VOLUME FLY ASH CONCRETE

FINAL REPORT

BY

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ABSTRACT

Concrete mixtures containing 340 kg/m³, 400 kg/m³ and 500 kg/m³ were studied for optimum replacement percentages of a low calcium fly ash. Extensive studies by CANMET has shown that replacement levels in the order of 56 percent by mass, will produce economical structural concrete.

The present study confirms that replacement levels in the order of 55 percent will minimize material costs per MPa for structural quality concrete. This conclusion is based on fly ash replacement levels varying from 45 to 60 percent and at water-cementitious ratios of 0.25, 0.27 and 0.32.



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INTRODUCTION

The development of structural concrete utilizing high volumes of low-calcium fly ash was undertaken by CANMET in 1985. The initial research was focused on developing a concrete mixture suitable for a ready-mixed concrete operation, and which would have a relatively low temperature rise for use in massive non-reinforced structural elements. This initial work utilized 55 to 56 percent (by mass of total cementitious) of low-calcium fly ash. Relatively high dosages of superplasticizers are used to obtain a water-to-cement ratio of less than 0.32 in this system. Extensive testing has shown that the mechanical properties and durability characteristics of high-volume fly ash concrete are equivalent to normal structural concrete. Since then, several structures with large diameter columns, beams and caissons utilizing high-volume fly ash concrete have been built in eastern Canada. The unit cost of high-volume fly ash concrete is significantly less than that of normal portland cement concrete.

The research described in this paper was performed to determine the optimum fly ash content in the high volume system. Optimum, for the purposes of this study is defined as the fly ash content for a given water-cementitious ratio which produces the most economical concrete on the basis of cost per MPa.

SCOPE OF STUDY

In this study, three series of concrete mixtures were evaluated. Series I contained a total cementitious content of 340 kg/m³, Series II contained a cementitious content of 400 kg/m³ and Series III contained a total cementitious of 500 kg/m³. Mixtures were performed at a water cementitious ratio of 0.27 and 0.32 at fly ash replacement (based on total cementitious) of 50, 55, 60 and 65 percent. A water-



cementitious ratio of 0.25 was also used in Series III mixtures. The fly ash content varied from 45 to 60 percent for these tests.

MATERIALS

Portland Cement

Normal Portland cement, ASTM Type I was used in the study. The physical and chemical properties of the cement are shown in Table 1.

Fly Ash

The fly ash used in the study was a low-calcium fly ash (ASTM Class F) from the coal fired thermal generating plant in Lingan, Nova Scotia. The characteristics of the fly ash are also shown in Table 1.

Coarse Aggregate

The coarse aggregate was a crushed and washed quartzite from a Halifax quarry, with a maximum size of 19 mm. The gradation and physical properties of the coarse aggregate are shown in Table 2.

Fine Aggregate

The fine aggregate was natural sand. The gradation and physical properties of the sand are shown in Table 3.



Superplasticizer

The superplasticizer (high-range water reducing admixture) was an aqueous solution of naphthalene sulphonate formaldehyde condensate. The solution contained 40 percent solids by mass.

Air-Entraining Admixtures

A neutralized Vinsol resin was used.

CONCRETE MIXTURES

The concrete mixtures were batched in a 0.15 m³ urich counter current mixer. Each batch of concrete was checked for slump, air content and mass density. The concrete mixture proportions and the properties of the fresh concrete are shown in Table 4 to 9, inclusive.

CASTING AND CURING OF TEST SPECIMENS

Compressive strength specimens (152 x 305 mm in size) were cast for laboratory storage and testing at 3, 7, 28, and 91 days. Three specimens were tested at each age.

DISCUSSION OF TEST RESULTS

Slump and Air Content

The concrete mixtures were proportional to provide a slump of 150 mm and air content of 6 ± 1 percent. The air content was relatively easy to achieve at modest amounts of air entraining agents. The slump increased significantly with increasing fly ash contents, for all cementitious contents, at fixed unit water content and superplasticizer addition.



Mechanical Properties of Cast Specimens Compressive Strength

The compressive strength data are given in Table 10, 11 and 12 for Series I, II and III, respectively. Each compressive strength value is the average of not less than three 152 x 305 mm cylinders. The compressive strength is shown graphically in Figures 1, 2 and 3. The strength data shows a high strength gain from 28 to 91 days, which is consistent with earlier studies on high volume fly ash concrete. Several significant conclusions on compressive strength can be drawn from this study.

1. At a fixed water-cementitious ratio, the compressive strength decreases with increasing cementitious content (See Figure 4). Thus, compressive strength is not only $W/C + F$ dependent, but the unit water content is an important factor.
2. For a given cementitious content, the compressive strength follows the general $W/C + F$ relationship as for conventional concrete (See Figure 5).
3. The ratio of the 91 day compressive strength, to the 28 day compressive strength decreases with increasing $W/C + F$ (See Figure 6).
4. At constant $W/C + F$, the ratio of the 91 day compressive strength to the 28 day compressive strength decreases dramatically with increasing cementitious content. (See Figure 7).
5. The optimum fly ash content, based on total cementitious is approximately 55 percent. (See Figures 8, 9 and 10). The optimization was based on material costs per MPa. By way of comparison, materials costs for conventional



concrete exceed the optimum high volume fly ash concrete by approximately 20 percent.

CONCLUSIONS

The compressive strength for the high volume fly ash system, based on material costs, is optimized at approximately 55 percent fly ash by mass of total cementitious content. This study has been conducted on one Portland cement and one Class F fly ash. Other cement and fly ash sources may affect the optimum results.

REFERENCES

Langley, W. S. "Structural Concrete Utilizing High Volumes of Low-Calcium Fly Ash"; International Workshop of the Use of Fly Ash, Slag and Silica Fume, Sydney, Australia, July 1988.

Langley, W. S., Carette, G. G., and Malhotra, V. M. "Structural Concrete Incorporating High Volumes of ASTM Class F, Fly Ash, ACI Materials Journal, Volume 86, NO. 5, 1989.



Table 1. Physical Properties and Chemical Analysis of Portland Cement and Fly Ash

	Normal Portland Cement ASTM Type I	Fly Ash Low Calcium (ASTM Class F)
<u>Physical Properties</u>		
<u>Fineness</u>		
Passing 45 μ m sieve	94.3 %	84%
Surface area, Blaine	368 m ² /kg	351 m ² /kg
<u>Vicat Setting Time</u> - initial		
- final	140 min. 280 min.	
<u>Compressive Strength</u>		
- 3 day	28.8 MPa	
- 7 day	33.3 MPa	
- 28 day	38.7 MPa	
<u>Pozzolanic Activity Index</u>		
- Water requirement		88%
- Activity Index, 28 day		97%
<u>Chemical Analysis</u>		
Silicon dioxide (SiO ₂)	21.26%	45.2%
Aluminum oxide (Al ₂ O ₃)	4.48%	20.7%
Ferric oxide (Fe ₂ O ₃)	1.71%	24.8%
Calcium oxide (CaO)	62.88%	1.63%
Magnesium oxide (MgO)	3.23%	0.97%
Sulphur trioxide (SO ₃)	2.35%	0.65%
Sodium oxide (Na ₂ O)	0.50%	0.59%
Potassium oxide (K ₂ O)	0.49%	2.40%
Loss on ignition	2.17%	2.66%
Insoluble Residue	0.67%	-
<u>Bogue Potential Compound Composition</u>		
C ₃ S	55.2%	
C ₂ S	19.3%	
C ₃ A	9.0%	
C ₄ AF	5.2%	

Table 2. Coarse Aggregate (Crushed Quartzite)

Gradation Analysis	
Sieve Size (mm)	Percent Finer
20	100.0
14	79.3
10	43.5
5	8.4
2.5	2.5
Relative Density (SSD) 2.71 Absorption (%) 0.39 Soundness (Na_2SO_4), Average Loss (%) 0.02 Los Angeles Abrasion Loss (%) 14.20	

Table 3. Properties of Fine Aggregate (Natural Sand)

Gradation Analysis	
Sieve Size (mm)	Percent Finer
10	100
5	98
2.5	89
1.25	70
0.630	43
0.315	18
0.160	5
Relative Density (SSD) 2.61 Absorption (%) 1.30 Soundness (Na_2SO_4), Average Loss (%) 6.33	

OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES I - CONCRETE MIXTURES

W/C+F Ratio	Fly Ash Replacement, %	Portland Cement kg/m³	Fly Ash kg/m³	Coarse Aggregate kg/m³	Fine Aggregate kg/m³	Water l/m³	Daravair ml/m³	WRDA 19 ml/m³
0.27	50	170	170	1100	838	92	410	12000
	55	153	187	1100	834	92	330	16000
	60	136	204	1100	832	92	400	16000
	65	119	221	1100	829	92	425	16000
0.32	50	168	168	1084	782	107	335	5000
	55	150	184	1079	775	107	375	5000
	60	135	203	1093	782	108	345	5000
	65	118	219	1088	776	108	345	5000

Table 4

OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES II - CONCRETE MIXTURES

W/C+F Ratio	Fly Ash Replacement, %	Portland Cement kg/m ³	Fly Ash kg/m ³	Coarse Aggregate kg/m ³	Fine Aggregate kg/m ³	Water l/m ³	Daravair ml/m ³	WRDA 19 ml/m ³
0.27	50	157	197	1081	725	106	500	8000
	55	178	217	1084	725	107	525	8000
	60	159	238	1091	726	107	610	8000
	65	140	260	1098	728	108	555	8000
0.32	50	196	196	1079	673	126	500	5775
	55	178	217	1086	674	126	390	4900
	60	158	236	1083	669	126	280	3330
	65	139	259	1095	673	127	390	5000

Table 5

OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES III - CONCRETE MIXTURES

W/C+F Ratio	Fly Ash Replacement, %	Portland Cement kg/m ³	Fly Ash kg/m ³	Coarse Aggregate kg/m ³	Fine Aggregate kg/m ³	Water l/m ³	Daravair ml/m ³	WRDA 19 ml/m ³
0.27	50	246	246	1080	568	133	725	5000
	55	222	275	1087	567	133	555	3890
	60	195	295	1083	561	133	555	4445
	65	172	319	1081	556	133	555	3890
0.32	50	243	243	1068	498	154	500	1110
	55	222	271	1084	500	157	500	1445
	60	198	291	1089	499	157	500	1445
	65	175	325	1101	501	158	500	1335

Table 6

OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES I - CONCRETE MIXTURES

W/C+F Ratio	Fly Ash Replacement, %	Ambient Temp., °C	Concrete Temp., °C	Initial Slump, mm	Final Slump, mm	Air Content, %	Mass Density kg/m³
0.27	50	21	21	0	0	5.1	2416
	55	18	21	0	0	5.5	2416
	60	18	21	0	0	5.8	2409
	65	18	21	0	0	5.8	2408
0.32	50	20	21	0	85	6.2	2377
	55	20	22	0	75	6.0	2384
	60	21	25	0	190	6.9	2352
	65	21	23	0	190	6.5	2359

Table 7

OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES II - CONCRETE MIXTURES

W/C+F Ratio	Fly Ash Replacement, %	Ambient Temp., °C	Concrete Temp., °C	Initial Slump, mm	Final Slump, mm	Air Content, %	Mass Density kg/m ³
0.27	50	20	25	0	65	6.0	2387
	55	20	23	0	90	6.0	2377
	60	20	23	0	110	6.5	2359
	65	20	25	0	150	6.5	2341
0.32	50	20	25	0	75	7.0	2359
	55	20	23	0	100	7.0	2341
	60	21	26	0	120	7.0	2345
	65	22	25	0	190	6.8	2316

Table 8

OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES III - CONCRETE MIXTURES

W/C+F Ratio	Fly Ash Replacement, %	Ambient Temp., °C	Concrete Temp., °C	Initial Slump, mm	Final Slump, mm	Air Content, %	Mass Density kg/m³
0.27	50	20	23	0	50	6.0	2355
	55	20	22	0	75	6.5	2338
	60	20	22	0	100	6.8	2341
	65	20	23	0	75	6.3	2341
0.32	50	20	23	0	75	6.5	2341
	55	20	22	0	125	6.6	2302
	60	20	22	0	120	6.6	2288
	65	20	20	0	125	7.0	2259

Table 9

**OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES I - COMPRESSIVE STRENGTH**

W/C+F Ratio	Fly Ash Replacement, %	Age, days			
		Compressive Strength, MPa (continuous moist curing)			
		3	7	28	91
0.27	50	25.2	32.6	46.6	67.5
	55	21.7	28.3	44.4	63.1
	60	18.4	25.0	41.2	58.4
	65	15.5	21.3	38.4	58.3
0.32	50	20.9	27.3	43.4	55.9
	55	17.9	24.8	39.1	54.9
	60	15.4	21.6	36.2	48.5
	65	12.3	17.8	33.0	44.2

Table 10

**OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES II - COMPRESSIVE STRENGTH**

W/C+F Ratio	Fly Ash Replacement, %	Age, days			
		Compressive Strength, MPa (continuous moist curing)			
		3	7	28	91
0.27	50	27.6	35.4	49.8	64.3
	55	25.3	32.3	47.0	61.5
	60	21.0	27.5	42.1	55.9
	65	16.2	23.4	39.4	51.8
0.32	50	21.9	27.6	40.4	51.9
	55	19.3	25.4	39.7	51.2
	60	14.9	20.3	34.5	43.1
	65	13.5	19.9	33.7	44.9

Table 11

**OPTIMIZATION OF HVFA CONCRETE MIXTURES
SERIES III - COMPRESSIVE STRENGTH**

W/C+F Ratio	Fly Ash Replacement, %	Age, days			
		Compressive Strength, MPa (continuous moist curing)			
		3	7	28	91
0.27	50	26.3	31.4	44.3	53.3
	55	24.1	30.1	43.7	51.9
	60	21.4	27.1	42.0	5.5
	65	16.1	21.9	36.1	42.8
0.32	50	15.5	20.3	30.8	37.6
	55	13.4	18.2	27.9	35.2
	60	12.4	19.1	26.2	37.4
	65	8.8	13.7	21.9	30.0

Table 12

SERIES I



FIGURE 1

SERIES II

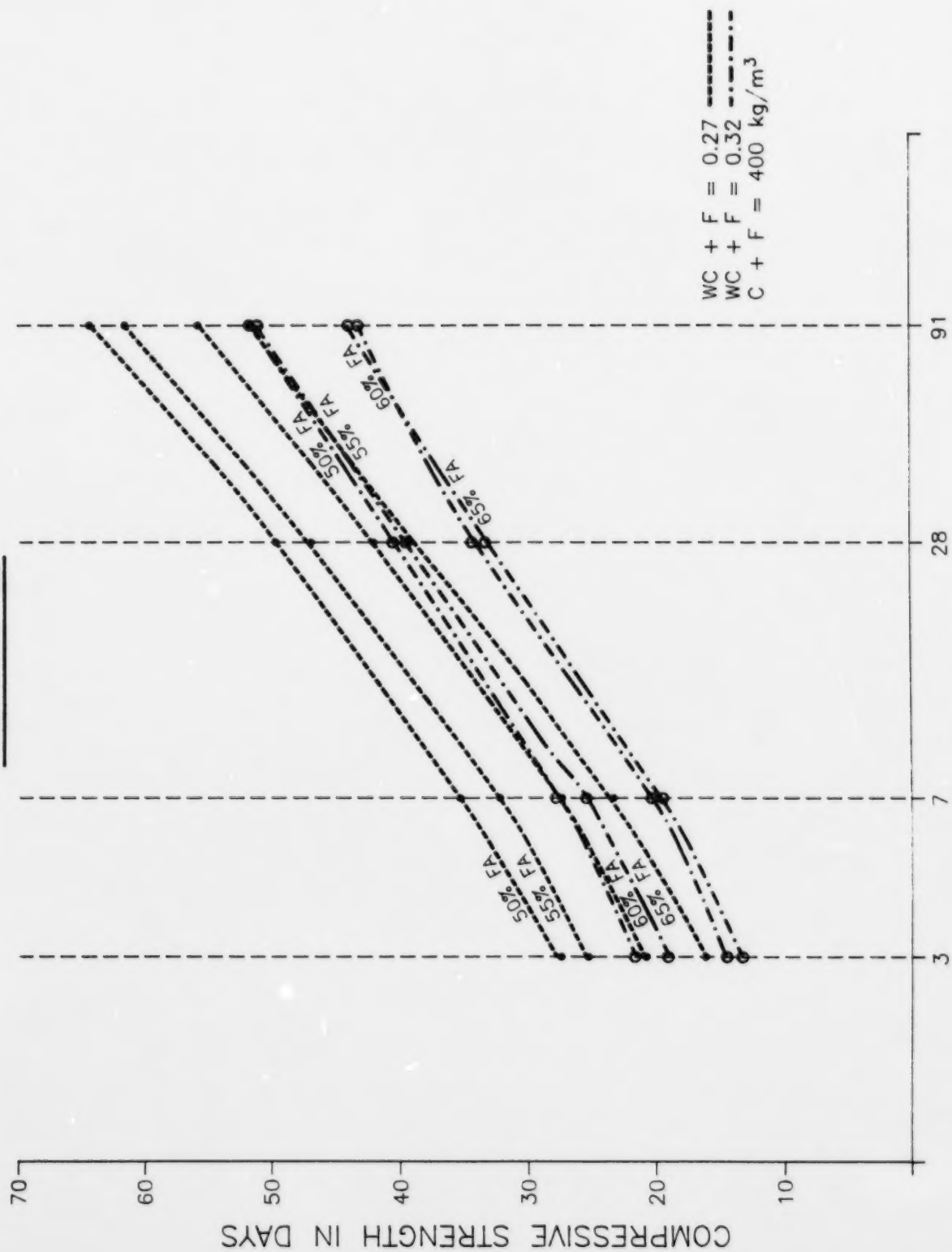


FIGURE 2

SERIES III

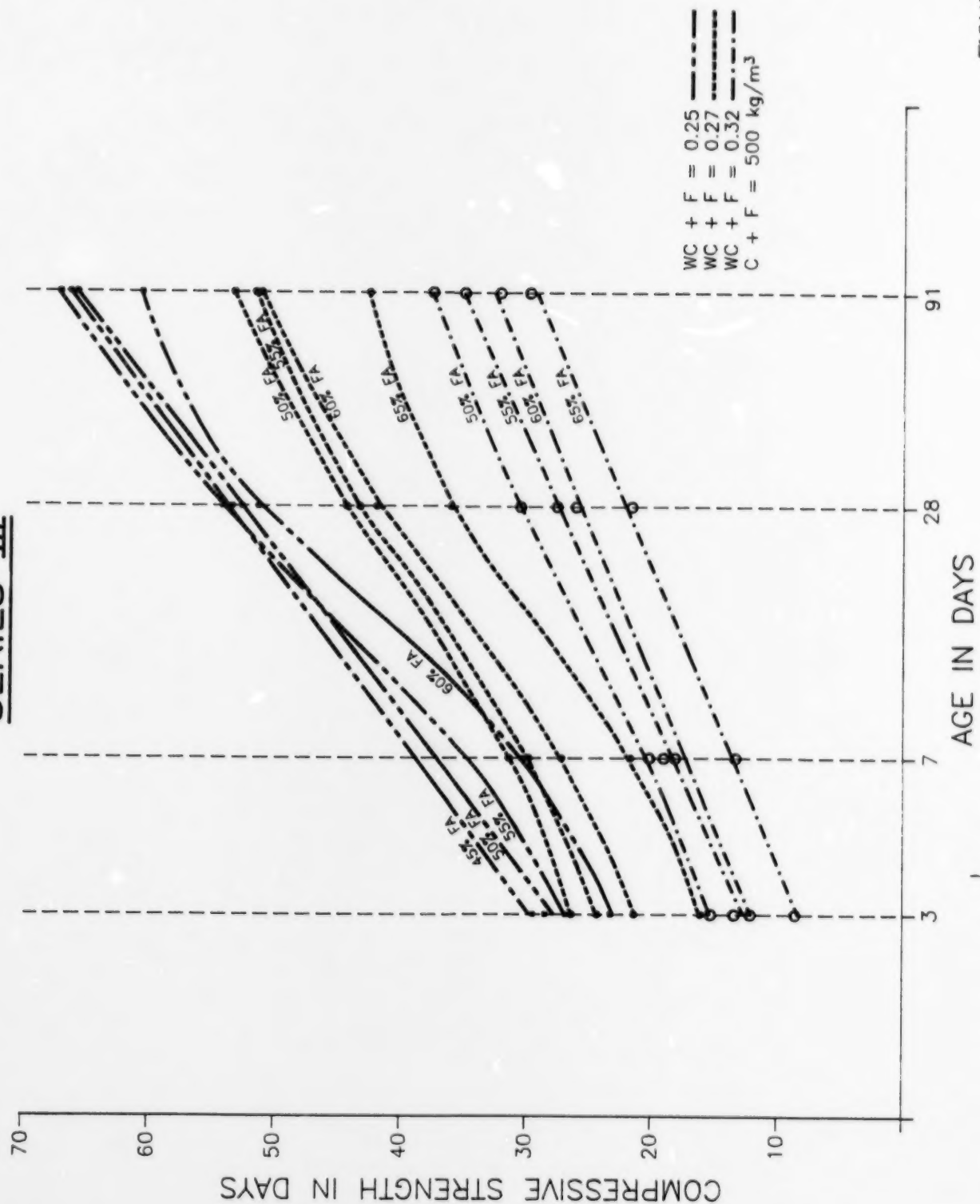


FIGURE 3

COMPRESSIVE STRENGTH VS. CEMENTITIOUS CONTENT

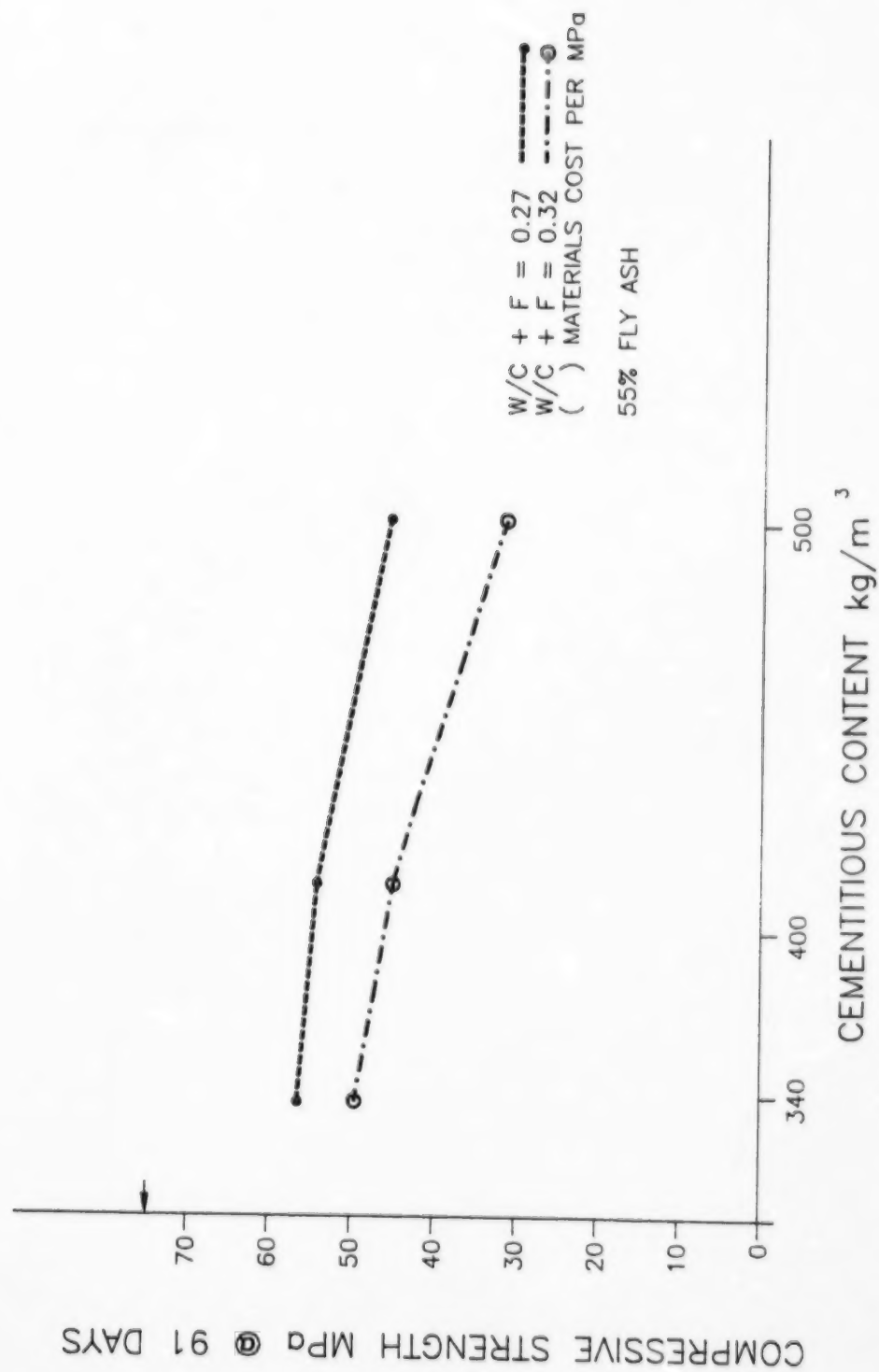


FIGURE 4

STRENGTH VS. W/C+F FOR 55 PERCENT FLY ASH

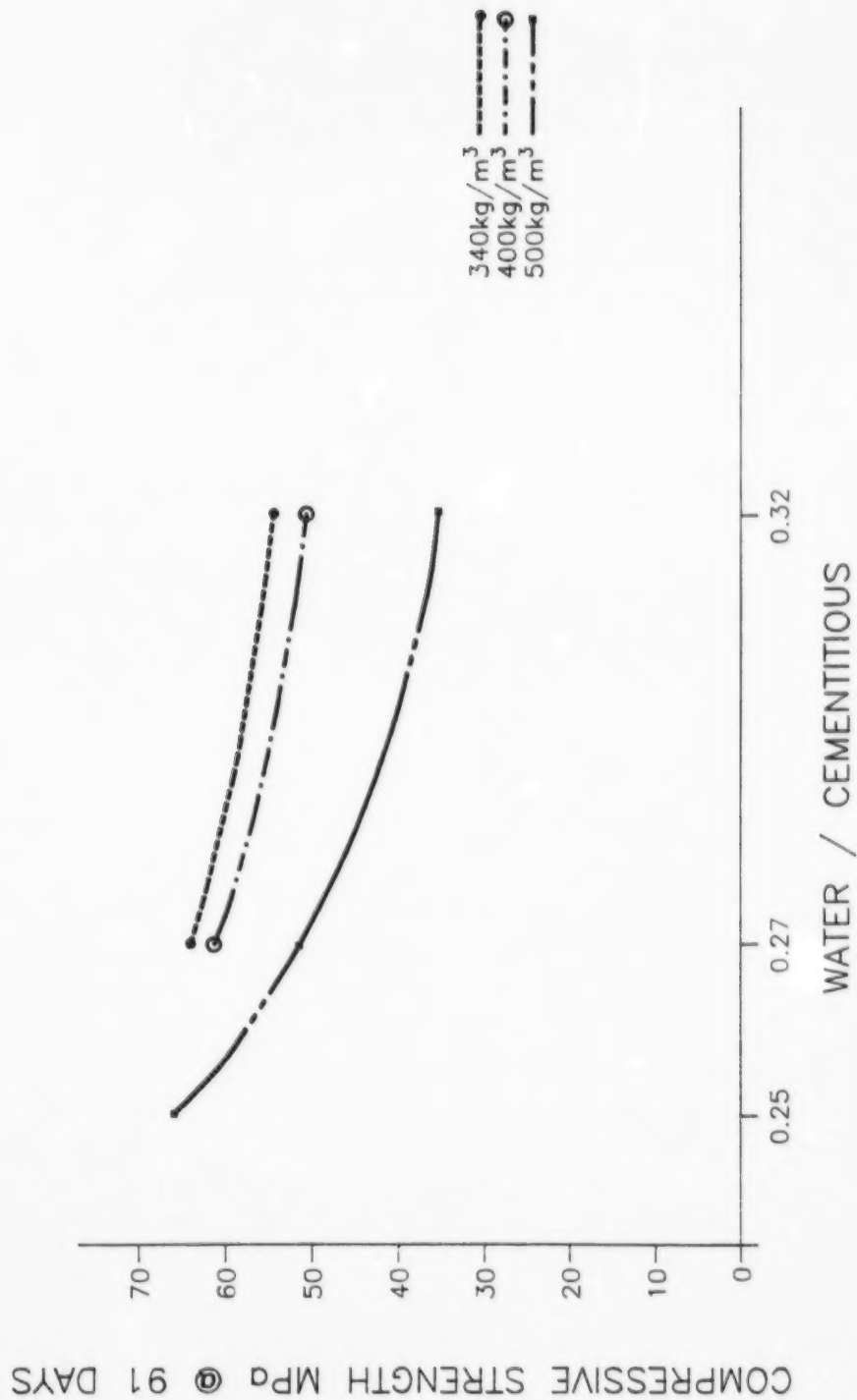


FIGURE 5

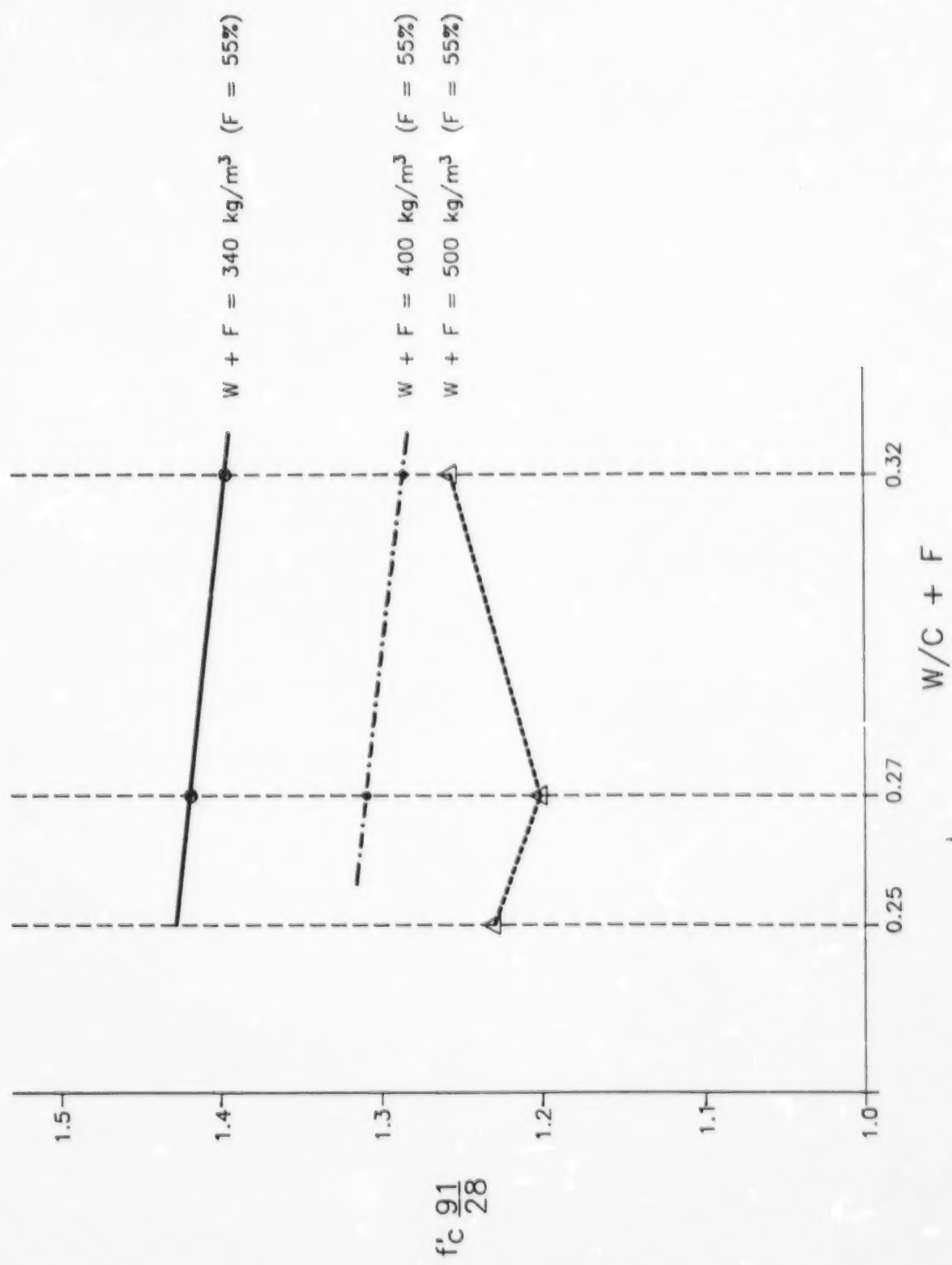


FIGURE 6

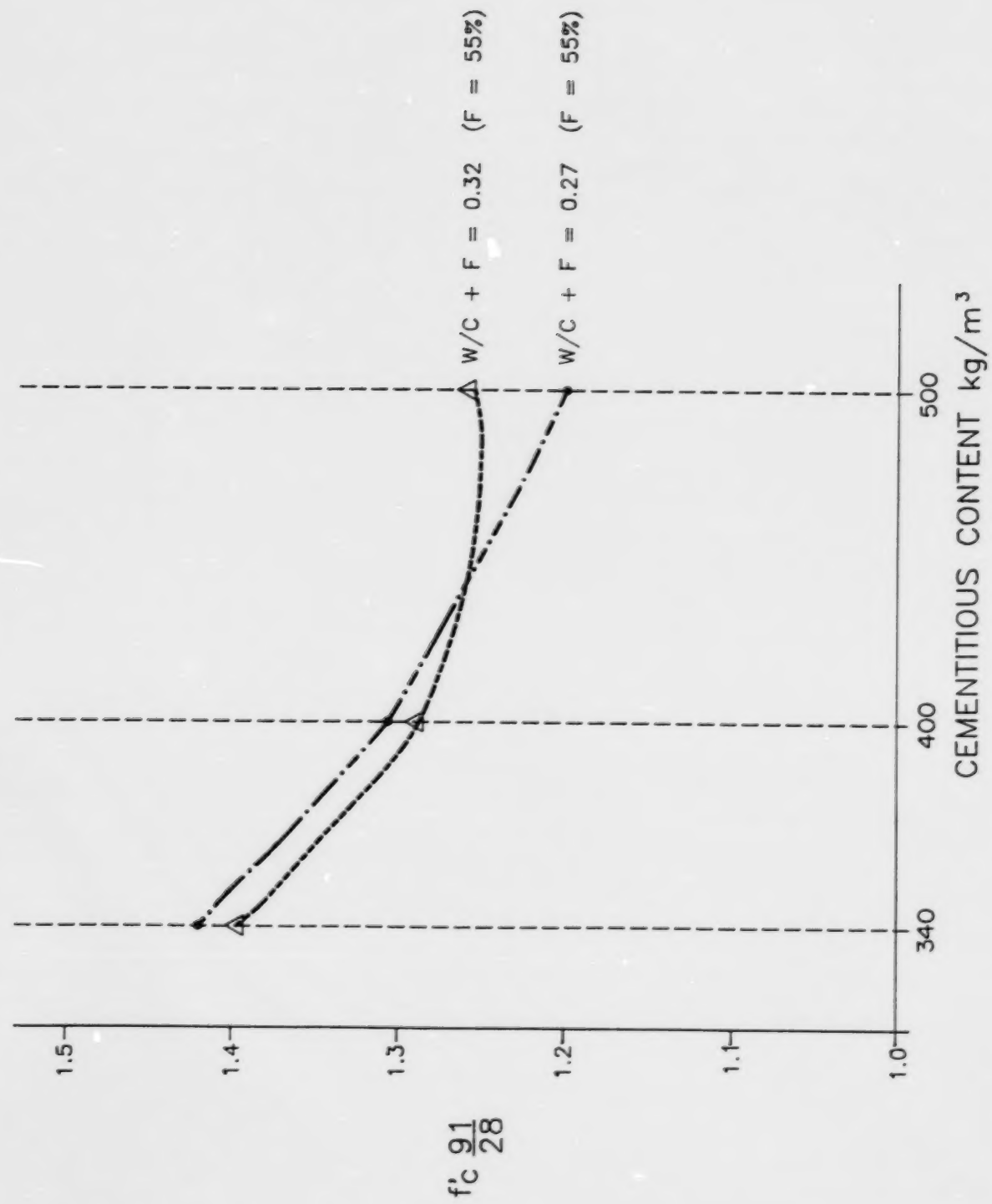


FIGURE 7

SERIES I MIXTURES

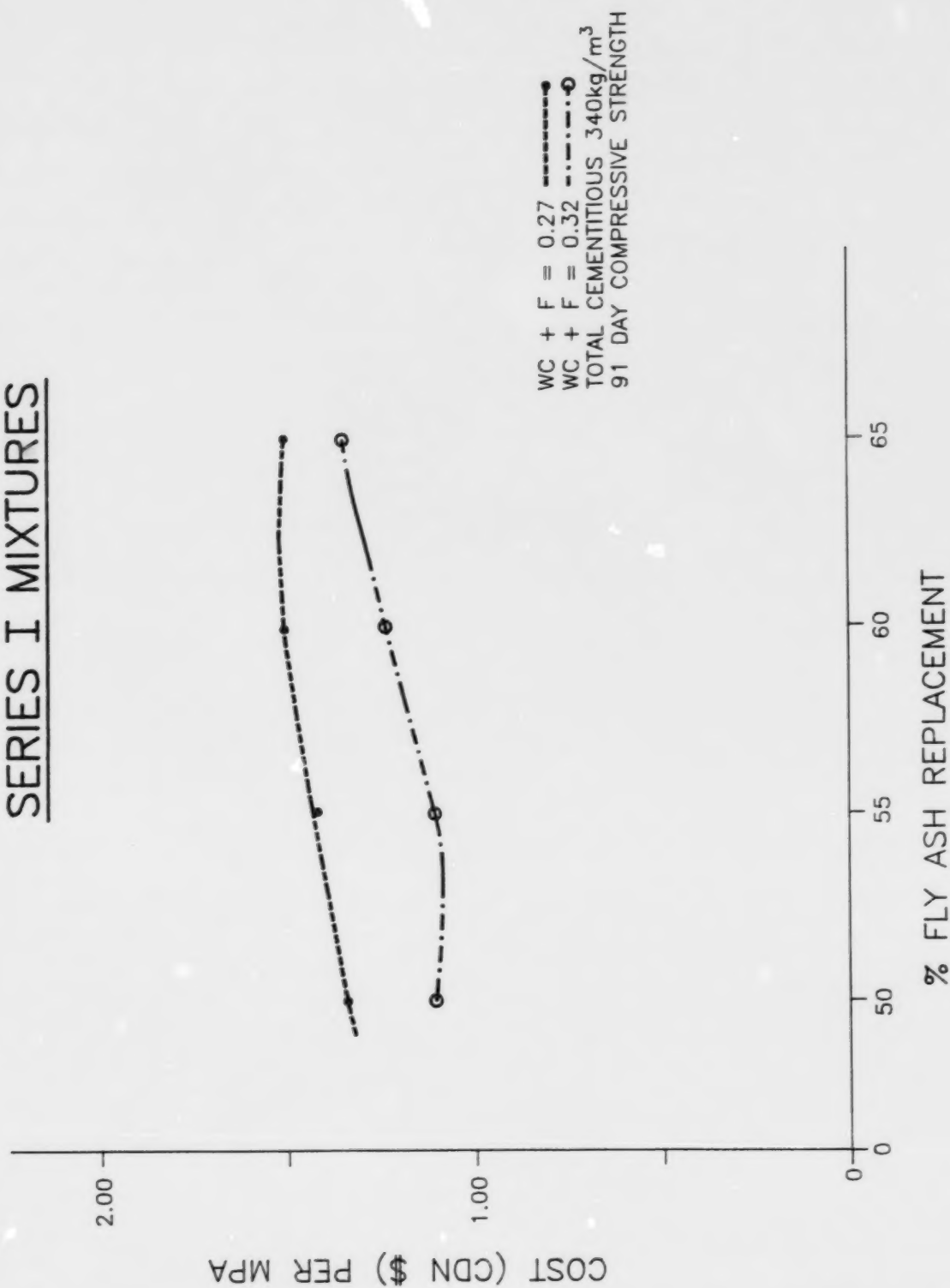


FIGURE 8

SERIES II MIXTURES

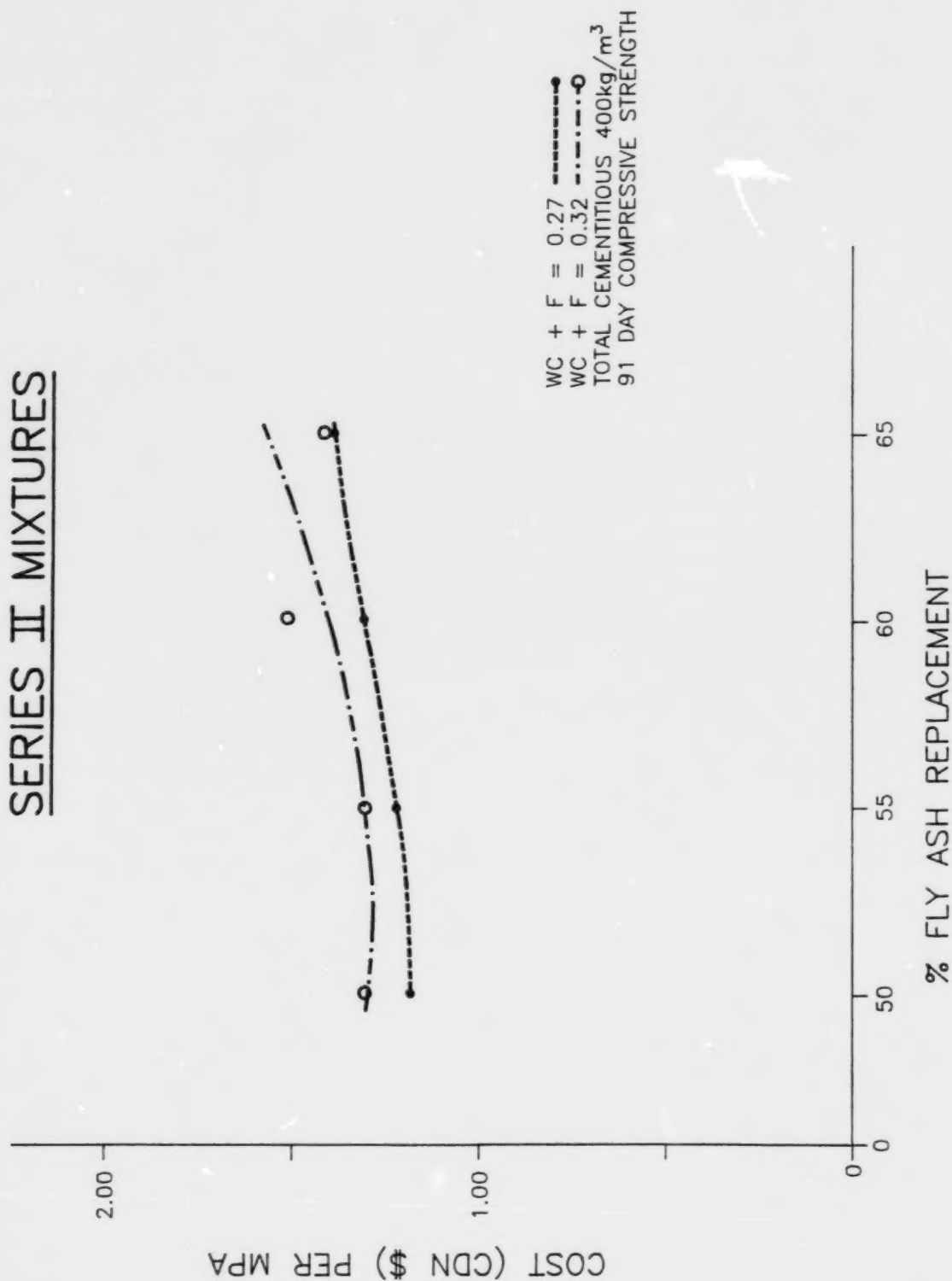


FIGURE 9

SERIES III MIXTURES

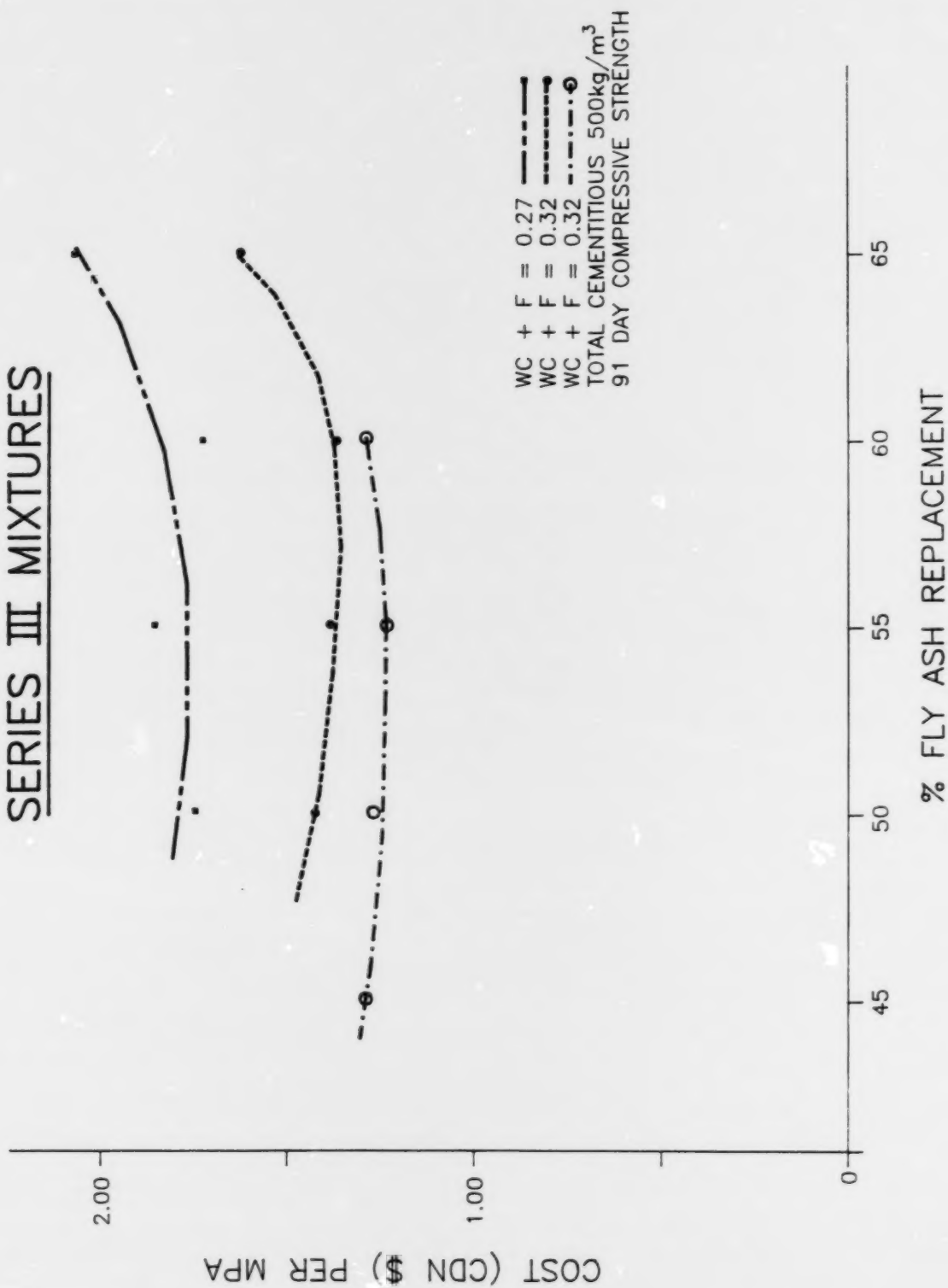


FIGURE 10

**TEST RESULTS OF FIELD DEMONSTRATION BLOCKS
UP TO THREE YEARS**



TABLE 3.4.27

HIGH VOLUME FLY ASH CONCRETE - DEMONSTRATION BLOCKS
HVFA (100 kg/m³ Portland Cement, 125 kg/m³ Fly Ash)

Test	Age						
	3d	7d	28d	91d	1y	2y	3y
SITE CURED SPECIMENS							
Compressive Strength	-	9.3	11.9	15.3	20.2	21.5	23.5
Carbonation	No	No	No	No	No	No	20 mm
Mass Density, kg/m ³	-	2227	2219	2339	2352	2288	-
Air Void Parameters							
Total Air, %	-	-	14.5	-	-	-	-
Specific Surface, mm ⁻¹	-	-	14.456	-	-	-	-
Spacing Factor, mm	-	-	0.081	-	-	-	-
LABORATORY CURED SPECIMENS							
Compressive Strength	-	-	22.1	35.5	50.8	58.9	61.3
Flexural Strength, MPa	-	-	-	5.6	6.3	-	-
Carbonation	No	No	No	No	No	No	No
Splitting Tensile, kPa	-	-	2090	2843	4113	-	-
Young's Modulus, GPa	-	-	27.9	-	27.2	-	36.9
Mass Density, kg/m ³	-	-	2297	2412	2293	2390	-
Air Void Parameters							
Total Air, %	-	-	8.9	-	-	-	-
Specific Surface, mm ⁻¹	-	-	8.83	-	-	-	-
Spacing Factor, mm	-	-	0.241	-	-	-	-
CORES DRILLED FROM BLOCKS							
Compressive Strength, MPa	-	-	17.4 ¹	24.2 ¹	34.8 ²	36.5 ²	-
Carbonation	-	No	No	No	No	No	8 mm
Young's Modulus, GPa	-	-	17.7 h	-	42.2 h	-	27.4h
	-	-	18.3 v	-	49.2 v	-	-
Mass Density, kg/m ³	-	-	2300	2374	2397	2352	-
Pulse Velocity, km/s	-	-	4.42 ¹	-	4.57 ³	4.56 ³	4.62 ⁴

1 = Average of three cores from the top of the block

2 = Average of all horizontal and vertical cores (s = 4.39 MPa)

3 = Average of all horizontal and vertical cores (s = 0.09 km/s)

4 = Average of all horizontal cores

h = Horizontal

v = Vertical



TABLE 3.4.25

HIGH VOLUME FLY ASH CONCRETE - DEMONSTRATION BLOCKS
HVFA (180 kg/m³ Portland Cement, 220 kg/m³ Fly Ash)

Test	Age						
	3d	7d	28d	91d	1y	2y	3y
SITE CURED SPECIMENS							
Compressive Strength	7.8	21.6	32.4	38.7	50.7	56.8	56.4
Carbonation	No	No	No	No	No	No	1 mm
Mass Density, kg/m ³	2243	2206	2220	2236	2217	2297	-
Air Void Parameters							
Total Air, %	-	-	11.0	-	-	-	-
Specific Surface, mm ⁻¹	-	-	18.75	-	-	-	-
Spacing Factor, mm	-	-	0.111	-	-	-	-
LABORATORY CURED SPECIMENS							
Compressive Strength	13.2	27.5	44.0	59.7	67.3	73.3	78.6
Flexural Strength, MPa	-	-	-	7.2	7.5	-	-
Carbonation	No	No	No	No	No	No	No
Splitting Tensile, kPa	-	-	3320	4020	5093	-	-
Young's Modulus, GPa	-	-	30.1	41.3	-	-	38.0
Mass Density, kg/m ³	2328	2292	2295	2362	2262	2332	-
Air Void Parameters							
Total Air, %	-	-	9.4	-	-	-	-
Specific Surface, mm ⁻¹	-	-	19.10	-	-	-	-
Spacing Factor, mm	-	-	0.125	-	-	-	-
CORES DRILLED FROM BLOCKS							
Compressive Strength, MPa	-	26.0	38.3 ¹	40.9 ¹	59.0 ²	67.7 ²	68.3 ⁴
Carbonation	-	No	No	No	No	No	1 mm
Young's Modulus, GPa	-	-	21.1 h	-	30.0 h	-	39.2h
	-	-	27.0 v	-	26.2 v	-	-
Mass Density, kg/m ³	-	2204	2279	2408	2375	2408	-
Pulse Velocity, km/s	-	4.22	4.61 ¹	-	4.68 ³	4.84 ³	4.88 ⁴

1 = Average of three cores from the top of the block

2 = Average of all horizontal and vertical cores (s = 4.39 MPa)

3 = Average of all horizontal and vertical cores (s = 0.09 km/s)

4 = Average of all horizontal cores

h = Horizontal

v = Vertical



TABLE 3.4.26

HIGH VOLUME FLY ASH CONCRETE – DEMONSTRATION BLOCKS
Control Mixture (400 kg/m³ Portland Cement)

Test	Age						
	3d	7d	28d	91d	1y	2y	3y
SITE CURED SPECIMENS							
Compressive Strength	26.6	34.2	41.9	44.4	47.3	51.3	50.4
Carbonation	No	No	No	No	No	No	1 mm
Mass Density, kg/m ³	2267	2230	2225	2344	2362	2318	-
Air Void Parameters							
Total Air, %	-	-	4.2	-	-	-	-
Specific Surface, mm ⁻¹	-	-	18.42	-	-	-	-
Spacing Factor, mm	-	-	0.287	-	-	-	-
LABORATORY CURED SPECIMENS							
Compressive Strength	31.0	36.0	44.9	50.0	56.0	55.0	53.4
Flexural Strength, MPa	-	-	-	7.1	6.9	-	-
Carbonation	No	No	No	No	No	No	No
Splitting Tensile, kPa	-	-	3470	3800	4673	-	-
Young's Modulus, GPa	-	-	34.4	-	34.1	-	-
Mass Density, kg/m ³	2286	2262	2264	2402	2286	2362	-
Air Void Parameters							
Total Air, %	-	-	5.4	-	-	-	-
Specific Surface, mm ⁻¹	-	-	20.63	-	-	-	-
Spacing Factor, mm	-	-	0.257	-	-	-	-
CORES DRILLED FROM BLOCKS							
Compressive Strength, MPa	-	35.0	34.8 ¹	36.7 ¹	45.3 ²	48.9 ³	46.3 ⁴
Carbonation	-	No	No	No	No	No	5 mm
Young's Modulus, GPa	-	-	26.4 h	-	26.4 h	-	30.9h
	-	-	27.4 v	-	27.7 v	-	-
Mass Density, kg/m ³	-	2204	2205	2355	2454	2362	-
Pulse Velocity, km/s	-	4.28	4.36 ¹	-	4.50 ³	4.60 ³	4.63 ⁴

1 = Average of all three cores from the top of the block

2 = Average of all horizontal and vertical cores (s = 4.39 MPa)

3 = Average of all horizontal and vertical cores (s = 0.09 km/s)

4 = Average of all horizontal cores

h = Horizontal

v = Vertical

